Recommendations For The Adaptation Planning Of Water Distribution Systems

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ABSTRACT

The rehabilitation and optimization of water distribution systems (WDSs), defined in the present study as adaptation process, are essential for a reliable water supply and a good quality of drinking water. Changing boundary conditions, such as demographic development, system expansion and convergence, etc. make the adaptation of WDSs unavoidable. In the present study, recommendations for an optimized adaptation planning are presented, including the process of performance assessment and the dealing with scarce data sets. As a first approach, a Priority Index for the selection of pipelines to be adapted has been defined. It comprises the criteria Hydraulics, Water Quality and Vulnerability. The overall objective of the present research project is to create a best-practice example for the adaptation planning of small- to large-sized WDSs. The recommended approach starts with the definition of the data base and concludes with the transition path from the actual to the target network. The proposed framework for adaptation planning comprises a global and transferable procedure, where a software component for hydraulic modelling, performance assessment, network optimization and data analysis is proposed, as a supporting tool for decision-makers and stake holders in the drinking water sector. The procedures have been partially verified on a case study.

Keywords: water distribution systems, small water supply systems, adaptation planning, performance assessment

1 Background

As the global water sector faces immense challenges, such as climate and demographic change, the adaptation of drinking water and sewer networks is currently one of the biggest tasks for municipalities and water companies. The critical issue is here that most of the systems were designed and built around 80 to 100 years ago, so that ageing, leaking pipelines and modified conditions are currently the consequence, if no proper rehabilitation takes place. In the drinking water sector, WDSs might significantly exceed their design lifespan leading to failure to meet the minimum level of service. With rehabilitation measures, water losses can be reduced by repairing or renewing damaged pipes. However, additional benefits can be achieved if the rehabilitation of a system is combined with optimization measures, as described in the work presented here. On the other side, from the financial point of view, WDSs represent a major asset of municipal public infrastructure, thus the costs requirements for upgrading the systems are exorbitant. In Germany, Switzerland and Austria, there is a high fragmentation and prevalence of small water utilities [1, 2, 3] with a water supply lower than $300.000\,\mathrm{m}^3$

per year. For this, a typical scenario is the cooperation of neighbouring municipalities and the integration of individual WDS into one system. Regarding the increasing legal and operational requirements for drinking water utilities (e.g. efficient use of water and energy, reliable and secure water supply), the benefits of inter-municipal cooperation do not only rely on the potential costs savings due to the shared operational and personal management, but also in the redundant operation of the systems. In general, the current investment backlog, as well as the willingness of decision-makers in municipal water companies to cooperate with other neighbouring companies, create a decisive window of opportunities for the adaptation of WDS. Here, long-term approaches that balance performance, risk and costs during the whole operational life of small to large-sized WDSs are needed [4].

The present study is part of the research project *AkWa* (German acronym for "Adaptation of Municipal Water Distribution Systems"), funded by the Bavarian Research Foundation, commenced in October 2016 and concluding on September 2019. The project aims the overall optimization of the adaptation process of WDSs and should create a best-practice example for the thousands of small municipal water supply companies that have the task of intensifying the inter-municipal cooperation in order to ensure the water supply. Here, a software tool for hydraulic modelling and data analysis is being developed. The recommended strategies are applied and verified on one water supply company in Southern Germany (case study). The results presented in this paper represent the preliminary outcome of *AkWa*.

2 Methodology

2.1 Combination of Rehabilitation and Optimization Strategies

Awareness about the need for long term adaptation planning has risen globally in the last decades, for this reason, research in the field of water distribution systems has focused on the exploration of optimization and rehabilitation strategies. The use of hydraulic modelling has become an essential tool, as an accurately calibrated model cannot only be employed to design a WDS, but to completely analyse different hydraulic configurations and scenarios and to assess their performance and vulnerability.

Based on the structural condition of the pipelines and other parameters of the water network (e.g. year of construction, material, surrounding environment, operational conditions), different statistical and physical failure models for predicting the deterioration of water distribution pipelines have been developed. An overview of them can be found in [5, 6, 7, 8, 9]. The main objective of the models is the determination of the optimal amount and timing of rehabilitation and the performance of risk analyses. Nevertheless, the presented approaches are usually infeasible in small to medium-sized water networks because of their high data demand [4, 1].

On the other hand, since the 1970s, important research has addressed the optimization of WDSs, especially the optimization of pipe dimensions and the pump operation, trying to find a trade-off between the costs and the hydraulic performance of the network. Optimization is defined as the process of maximizing or minimizing an objective function under a set of boundary conditions. The tree main optimization procedures reported for WDSs in the literature are: deterministic (e.g. enumeration, linear programming), non-gradient (e.g. Genetic Algorithms) and real-time optimization [10, 11, 12, 13]. Apart from their complexity and usually high computing time, a weakness of the algorithms is that the physical condition of the infrastructure to be optimized is not being considered

[13].

In the present study, the term adaptation planning comprises both, the process of rehabilitation and the structural optimization of WDSs for facing future challenges. The first step is here the development of a Priority Index for the selection of the pipelines to be adapted (i.e. to be rehabilitated with an optimal pipe diameter), as described in the following chapter.

2.2 Criteria for the Assessment of WDSs

The performance assessment of WDSs serves as basis for adaptation planning. It is based on the definition of performance indicators for allowing the quantitative evaluation of the efficiency or effectiveness of a system or process [14], and is currently a established practice in the management of water and waste water networks. In the present study, performance assessment supports the definition of the overall adaptation target, as well as the decision-making for selecting an optimal network. Here, the five criteria Hydraulics, Quality, Vulnerability, Supply Efficiency and Finances were identified, as shown in table 1. The selected performance indicators are related to the nodes (k), pipelines (i), single tanks or to the complete water network (total).

Table 1: Criteria and performance indicators for the assessment of WDSs

Criteria	Indicator	Description
Hydraulics (H)	$p_{min,k}$	minimal pressure
	$p_{min,fire,k}$	minimal pressure in fire case
	$p_{max,k}$	maximal pressure
	$v_{max,i}$	maximal velocity
Quality (Q)	$v_{min,s,i}$	minimal velocity for preventing stagnation
	$v_{min,d,i}$	minimal velocity in ductile pipes for preventing mineral deposition
	$t_{max,tank}$	maximal retention time in tanks
Vulnerability (V)	c_i	relative condition indicator
	b_i	importance of pipelines
Supply efficiency (E)	$q_{loss,total}$	amount of water losses in the network
	e_{total}	total energy consumption in the network
Finances (F)	c_{total}	total costs
	r_{total}	rehabilitation rate

The criteria Hydraulics and Quality describe the operative performance of the water network, and the corresponding indicators can be calculated using a calibrated hydraulic model. For these parameters, the fulfilment of the minimum or maximum allowed values can be described by so-called *performance curves*, which produce performance values from 0 % (no service) to 100 % (maximum or optimal service) [15, 16]. In order to compute global performance indicators for the entire network, generalization operators are applied as recommended by [16]. Here, the indicators of single elements are summed up considering weight factors (consumption for nodes and water volume for pipelines) for computing a global network performance.

The criteria Vulnerability comprises the indicators Condition (c) and Importance (b) of the pipelines. In the present study, the indicator c describes the relative condition status of the pipelines and can be simplified assumed as

$$c_i = RN_i/N_i - S_i \tag{1}$$

based on the pipe age (rest lifespan RN and economic lifespan N) and on the identified failure events (S), if the data is provided. For the failure discount factor S, the tree ranges low, middle and high failure rate are defined.

The Importance (b) of the pipelines describes the effects of the failure of the pipeline i on the entire WDS and is calculated as

$$b_i = 1 - ((Q_{u,i}/Q_{total}) - A_{crit}) \tag{2}$$

based on the ratio of non-provided water amount by failure of the pipeline i ($Q_{u,i}$) and total demand (Q_{total}), and on the discount factor A_{crit} for the affected critical infrastructures (e.g. hospitals).

The Priority Index (P) for rehabilitation and diameter optimization of water pipelines comprises the criteria Hydraulics (H), Quality (Q) and Vulnerability (V) and is defined as

$$P_i = W_H \cdot H_i + W_Q \cdot Q_i + W_V \cdot V_i = W_H \cdot H_i + W_Q \cdot Q_i + W_c \cdot c_i + W_b \cdot b_i \tag{3}$$

The weight factors W depend on the long-term objectives of the water utility. Similarly, each indicator of table 1 can be weight up, according to the operative targets of the company.

Indicators to quantify the Supply Efficiency (amount of real water losses, overall energy demand) and the Finances of the water utility (total system costs, rehabilitation rate), are currently not used as criteria within the optimization procedure. These will be used in the next project phase to compare different system configurations and operating strategies.

2.3 Availability of Data for Hydraulic Modelling and Assessment of WDSs

In general, the results of hydraulic modelling and the decision process for planning adaptation measures depend strongly on the amount and quality of the available data. Data of insufficient accuracy can lead to wrong decisions. For the present approach, available information can be divided in necessary and recommended data.

Necessary Data: Setting up a calibrated hydraulic model requires at least information on the network topology (pipelines: dimension, material; nodes: geodetic altitude; tanks: volume, water level, etc.), on the water consumption amount (domestic and bulk consumers) and recorded data during measuring campaigns for model calibration. For a cost-effective planning, pipe age and rehabilitation costs are additionally needed.

Recommended Data: To increase the quality of the hydraulic model and for a reliable decision-making, utility-dependent guidelines and performance curves, water consumption per house connection and daily domestic consume patterns are needed, as well as statistics to failure events, rest and economic lifespan of pipelines and cost saving factors (e.g. synergies with other roadworks).

As a consequence of the limited data availability, especially in small water utilities, additional information sources and methods on how to cope with the data gaps are needed. Sources of information for missing data (pipe age, material, diameter) can be historical documents on development plans, documentation of sewer networks or documentation on repaired pipe damages. If the data is still not available, the indicators (for instance the Condition indicator c) might be adjusted to the lowest value (worst-case scenario). After the calculations for adaptation planning have been performed, the accuracy or uncertainty of the results is to be analysed.

2.4 Software Component as Supporting Tool

In order to implement the assessment process proposed in section 2.2 and integrate it in the adaptation process, a software tool is being developed. It consists of the GIS software AQUA++[1], that interacts with the widely used hydraulic modelling software EPANET2 [17] and a module for WDS optimization and evaluation, developed in the frame of the *AkWa* project. This module will be designed as an open source tool. The described performance assessment is automatized and thus is being fully implemented in the software tool. For the hydraulic evaluation of the network, the EPANET2 toolkit is used for all hydraulic calculations. The toolkit is a program library that allows the direct in-memory manipulation and hydraulic recalculation of the EPANET network model [18]. This is a key process for achieving a performant calculation, because of the iterative optimization and evaluation procedure.

In general, the following tasks are carried out by the developed software tool:

1. Collection and management of necessary and recommended data (data import), and visualization and aggregation of data (data manager)
2. Management of WDS variants (scenario manager)
3. Performance assessment of WDSs (status assessment, vulnerability analysis, sensitivity analysis, cost analysis)
4. Algorithmic optimization of WDSs

As tasks 1 is more or less a standard GIS functionality, AQUA++ provides it mostly out-of-the-box. Because of the iterative nature of the optimization process, the management of network variants is a prerequisite for a GIS based WDS optimization. The scenario and data manager also allows a visualization and clear evaluation in tabular form (as in table 2) of the different adaptation results and thus support civil planners in comparing current and target networks.

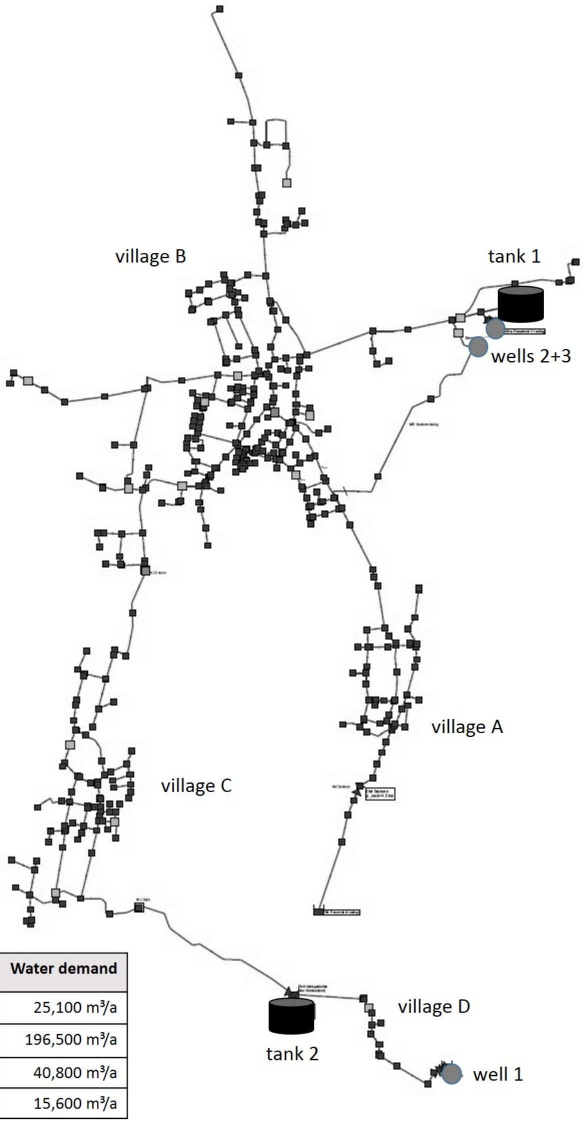
3 Results

3.1 Case Study

For verifying the presented approach, the performance of a real water network located in Southern Germany is currently being evaluated (see figure 1). For this study, the analysed supply area is composed of four villages and three pressure zones with a total length of approx. $42\,\mathrm{km}$. The system

[1] AQUA++ is a software product of the company tandler.com GmbH

provides $280.000\,\mathrm{m}^3$ water per year to about 4,500 consumers (mostly rural, no bulk consumers). For calibrating the hydraulic model, a measuring campaign of one week was started, using pressure loggers located at strategic nodes in the network. Here, modelled and measured data were compared in order to verify the input data and determine the friction coefficient of the pipelines. Unfortunately, the data on pipe ages, failure events and construction costs is currently being processed and could not be evaluated for this study. For this, the performance assessment of the case study includes solely the criteria Hydraulics and Quality. The results are shown in table 2.



	Inhabitants	Water demand
A	456	25,100 m³/a
B	3,280	196,500 m³/a
C	776	40,800 m³/a
D	221	15,600 m³/a

Figure 1: Water distribution network of study case

For the analysed WDS, the pressure requirements ($p_{min,k}$, $p_{min,fire,k}$ and $p_{max,k}$) are almost fulfilled for all demand scenarios. However, there are single nodes in village B showing deficits at maximum water demand and in fire case. Regarding the flow velocity, the maximum allowed value is fulfilled for all scenarios. Nevertheless, the minimum velocity for preventing stagnation and mineral deposition is violated in all villages. To sum up, the results of performance assessment indicate over- and undersized pipelines that cause deficits in the pipe velocity and in the operational pressure. The conflict between low velocities and low operational pressure heads is a typical dilemma for water utilities, especially in rural areas. In general, stagnation and deposition in ferric pipes might be improved by

Table 2: Performance assessment for case study

Criteria	Indicator	Limit value [1]	Network performance
Hydraulics (H)	$p_{min,k}$	$(2 + 0.5 \cdot NS)$bar [2]	98,6 %
	$p_{min,fire,k}$	$1.5\,\text{bar}$	98,1 %
	$p_{max,k}$	$8.0\,\text{bar}$	100 %
	$v_{max,i}$	$2.0\,\text{m}\,\text{s}^{-1}$	100 %
Quality (Q)	$v_{min,s,i}$	$0.005\,\text{m}\,\text{s}^{-1}$	91,6 %
	$v_{min,d,i}$	$0.3\,\text{m}\,\text{s}^{-1}$	63,2 %
	$t_{max,tank}$	$5 - 7\,\text{d}$	100 %

[1] acc. to DVGW guidelines (German Technical and Scientific Association for Gas and Water)

[2] NS: number of storeys

punctual reduction of the pipe diameters or by periodical flushing of the segments. For alleviating the pressure problem, apart from increasing the pipe dimensions, the optimization of pressure zones (location and settings of tanks, valves and pumps) or alternative water reservoirs for the fire case should be weight up.

Before starting the adaptation planning of the WDSs as an automatic procedure, overall structural optimizations (alternative tank locations) are being evaluated using the calibrated hydraulic model shown in figure 1. This essential step for the planning engineer requires the expertise of the water utility. At this point, it could be confirmed that a software feature that allows an abstraction and simplification of the hydraulic model is very useful, as a basis for discussion between water company, engineering consultants and other decision-makers.

3.2 Recommended Approach for Adaptation Planning

The authors of this paper propose a new framework for strategic adaptation planning, supported by a software tool for hydraulic modelling, performance assessment and data analysis, as described in section 2.4 and shown in figure 2. First step of the approach is the definition of the targets for the adaptation planning (operation, system reliability, supply efficiency or financial aspects). A scenario and data manager is used to manage the required data for subsequent calculations. The second component comprises performance and condition assessment of the current WDS, where the hydraulic minimum requirements are analysed. Based on the current status of the WDS and the determined targets, optimization calculations are performed and various network variants are generated. All network variants are subjected to assessment of hydraulic and condition performance. Afterwards, sensitivity and costs analysis support the selection of the target network by the planer together with the water supply company. Condition analysis of the pipelines is considered in order to prioritize the adaptation measures (at first pipeline's renewal with current or optimized diameter). The adaptation process concludes with a sequence of adaptation measures (transition path) for planning the migration from the current to the target network.

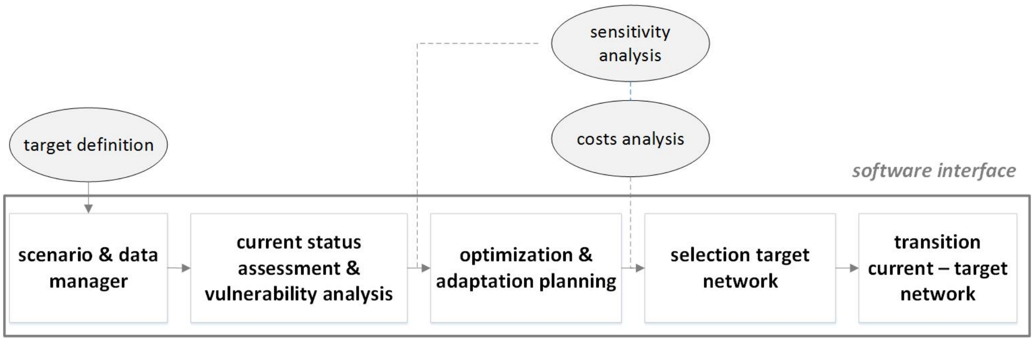


Figure 2: Proposed approach for adaptation planning of WDSs

4 Conclusions

This paper presents a framework for the strategic adaptation planning of WDSs, valid also for small-sized water utilities and poor data sets. The recommended approach comprises a global and transferable procedure that involves the view of research, water utility and planning engineers and aims to support decision-makers and stake holders in the drinking water sector, in joining and adapting their WDSs cost-effectively. With the aim of combining optimization and rehabilitation strategies, a Priority Index, that considers the network criteria Hydraulics, Water Quality and Vulnerability has been defined. The objective here is to include the condition of the water pipelines in the optimization process. For ensuring the accuracy of the results of hydraulic modelling and performance assessment, a minimum amount of data is needed, however the reliability of the calculations can be improved if additional data (performance curves, detailed water consumption patterns, statistics on failure events, etc.) is provided. Further, the preliminary results of the presented research project confirm that a software module for hydraulic modelling, performance assessment, network optimization and data analysis might be a very useful tool. Nevertheless, the manual network evaluation and the intensive knowledge exchange with the water utility are indispensable, as the optimization process of a water network can not be understood as a completely automatic procedure.

References

[1] L. Scholten, A. Scheidegger, P. Reichert, M. Mauer, and J. Lienert, "Strategic rehabilitation planning of piped water networks using multi-criteria decision analysis," *Water research*, vol. 49, pp. 124–143, 2014.

[2] G. Gangl and J. Koelbl, "Anwendbarkeit des infrastructure leackage index: ili für kleinere versorger und messzonen," in *Unterirdische Infrastruktur*, ser. Gwf Praxiswissen, C. Ziegler, Ed. München: Oldenbourg Industrieverl., 2012, vol. 5.

[3] BDEW, *Branchenbild der deutschen Wasserwirtschaft*. Bonn: Wirtschafts- u. Verlagsges. Gas u. Wasser, 2015.

[4] H. Alegre, "Is strategic asset management applicable to small and medium utilities?" *Water science and technology : a journal of the International Association on Water Pollution Research*, vol. 62, no. 9, pp. 2051–2058, 2010.

[5] Y. Kleiner and B. Rajani, "Comprehensive review of structural deterioration of water mains: Statistical models," *Urban Water*, vol. 3, no. 3, pp. 131–150, 2001.

[6] B. Rajani and Y. Kleiner, "Comprehensive review of structural deterioration of water mains: Physically based models," *Urban Water*, vol. 3, no. 3, pp. 151–164, 2001.

[7] Z. Liu, Y. Kleiner, B. Rajani, L. Wang, and W. Condit, *Condition Assessment Technologies for Water Transmission and Distribution Systems*. Office of Research and Development and National Risk Management Research Laboratory - Water Supply and Water Resources Division, 2012.

[8] F. Friedl, *Vergleich von statistischen und physikalischen Modellen zur Berechnung der Auftrittswahrscheinlichkeit von Schadensarten auf Trinkwasser-Haupt- und Zubringerleitungen*, ser. Schriftenreihe zur Wasserwirtschaft. Graz: Verl. der Techn. Univ. Graz, 2014, vol. 69.

[9] A. Scheidegger, J. P. Leitao, and L. Scholten, "Statistical failure models for water distribution pipes - a review from a unified perspective," *Water research*, vol. 83, pp. 237–247, 2015.

[10] D. Savic and G. Walters, "Genetic algorithms for least-cost design of water distribution networks," *Journal of Water Resources Planning and Management*, no. 123, pp. 67–77, 1997.

[11] W. Zhao, T. H. Beach, and Y. Rezgui, "Optimization of potable water distribution and wastewater collection networks: A systematic review and future research directions," *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, vol. 46, no. 5, pp. 659–681, 2016.

[12] H. Mala-Jetmarova, N. Sultanova, and D. Savic, "Lost in optimisation of water distribution systems? a literature review of system operation," *Environmental Modelling & Software*, vol. 93, pp. 209–254, 2017.

[13] N. Balekelayi and S. Tesfamariam, "Optimization techniques used in design and operations of water distribution networks: A review and comparative study," *Sustainable and Resilient Infrastructure*, vol. 2, no. 4, pp. 153–168, 2017.

[14] H. Alegre and S. T. Coelho, "Infrastructure asset management of urban water systems," in *Water Supply System Analysis - Selected Topics*, A. Ostfeld, Ed. InTech, 2012, pp. 49–73. [Online]. Available: https://www.intechopen.com/books/water-supply-system-analysis-selected-topics/infrastructure-asset-management-of-urban-water-systems

[15] P. M. Vidigal, D. Loureiro, and D. Covas, "Extended analysis of technical-hydraulic parameters and performance assessment in water distribution systems," pp. 1–10, 2008. [Online]. Available: https://fenix.tecnico.ulisboa.pt/downloadFile/395137903517/2008-12-22%20ExtendedAbstract_PedroVidigal_49232.pdf.pdf

[16] J. Muranho, A. Ferreira, J. Sousa, A. Gomes, and A. S. Marques, "Technical performance evaluation of water distribution networks based on epanet," *Procedia Engineering*, vol. 70, pp. 1201–1210, 2014.

[17] L. A. Rossman, "Epanet 2, users manual," 2000.

[18] ——, "The epanet programmer's toolkit for analysis of water distribution systems," in *Preparing for the 21st century*, E. M. Wilson, Ed. New York, N.Y.: ASCE, 1999, pp. 1–10.